

Q-switch Saturable Absorber Materials for Solid State Lasers

ROBERT D. STULTZ*, MARLY B. CAMARGO, AND MILTON BIRNBAUM

Center for Laser Studies, University of Southern California, DRB 17, University Park, Los Angeles, CA
90089-1112

* also with Hughes Aircraft Company at El Segundo, CA 90245

ABSTRACT

New solid-state passive Q-switch materials for the Er:glass laser at 1.53 μm are described. Saturable absorber Q-switching has been obtained using $\text{U}^{4+}:\text{SrF}_2$, $\text{Er}^{3+}:\text{CaF}_2$, and $\text{Er}^{3+}:\text{Ca}_5(\text{PO}_4)_3\text{F}$.

1. INTRODUCTION

Er:glass lasers are important in many applications because they emit in a narrow eye-safe spectral region around 1.54 μm . Uses for eyesafe lasers include communications, optical atmospheric remote sensing, and lidar applications.^{1,2} Many of these applications require short pulses with high peak power which can be obtained by Q-switching the Er:glass laser.

Saturable absorber Q-switching is simple and inexpensive, when compared to mechanical, electro-optical or acousto-optical Q-switch devices. Recently, our group reported saturable absorber Q-switching Er:glass laser using $\text{Er}:\text{Ca}_5(\text{PO}_4)_3\text{F}$ (or Er:FAP).³ Additional passive Q-switches for Er:glass ($\text{Er}^{3+}:\text{CaF}_2$ and $\text{U}^{4+}:\text{SrF}_2$),⁴ as well as new results with Er:FAP are described.

2. SATURABLE-ABSORBER Q-SWITCH THEORY

Saturable absorber Q-switching, for a 3-level laser, can be described using the following coupled differential equations:^{5,6}

$$\frac{dn}{dt} = [K_g N_g - K_a N_a - \gamma_c] n \quad (1)$$

$$\frac{dN_g}{dt} = -\gamma K_g N_g n \quad (2)$$

$$\frac{dN_a}{dt} = -K_a N_a n \quad (3)$$

where n is the cavity photon number, $K_i = \sigma_i/t_1 A_i$ ($i = g,a$), $\sigma_{g,a}$ are the stimulated emission and absorption cross-sections for the gain and saturable absorber media, respectively, and t_1 is the single-pass photon transit time. $A_{g,a}$ are the areas of the laser beam in the gain and absorber media, $N_{g,a}$ are the population differences for the gain medium and saturable absorber, respectively, and γ_c is the resonator cavity photon decay rate. $\gamma = 1 + g_2/g_1$, where $g_{1,2}$ are the lower, upper laser level degeneracies (for Er:glass, at room temperature, $\gamma \approx 2$). The lifetime of the laser and absorber excited-states have been assumed to be long compared to the Q-switch pulse duration. The absorber is assumed to be 3-level (i.e., the upper level of the absorption transition quickly decays to a second excited-state level and there is no excited-state absorption).

For a slow acting saturable absorber, the excited-state decay time is long compared with the Q-switch pulse of the laser. Then, the absorber cross-section must satisfy the following:^{5,6}

$$\sigma_a > \frac{\gamma A_a}{A_g} \sigma_g \quad (4)$$

If $\sigma_a = \gamma \sigma_g$, then the laser beam must be concentrated to a smaller region in the Q-switch than in the gain medium (i.e. $A_a < A_g$), in order to achieve Q-switching. This is the case with $\text{Er}^{3+}:\text{CaF}_2$ and $\text{Er}^{3+}:\text{FAP}$ where intracavity focussing is required. However, the cross-section of $\text{U}^{4+}:\text{SrF}_2$ is sufficiently high to allow Q-switching without intracavity focussing. Numerical solution of equations 1 to 3 provided results in good agreement with the experimental results

3. EXPERIMENTAL RESULTS

3.1. Bleaching measurements

The absorption spectrum for each of the Q-switch materials is shown in Figure 1. Values for the absorber cross-sections were obtained by measuring the saturation fluence for each of the Q-switch materials at 1543 nm using a Raman-shifted Nd:YAG laser. The pulsewidth of the Raman laser was about 15 nsec (short compared to the absorber lifetimes), and its spectral linewidth was less than 1 nanometer.

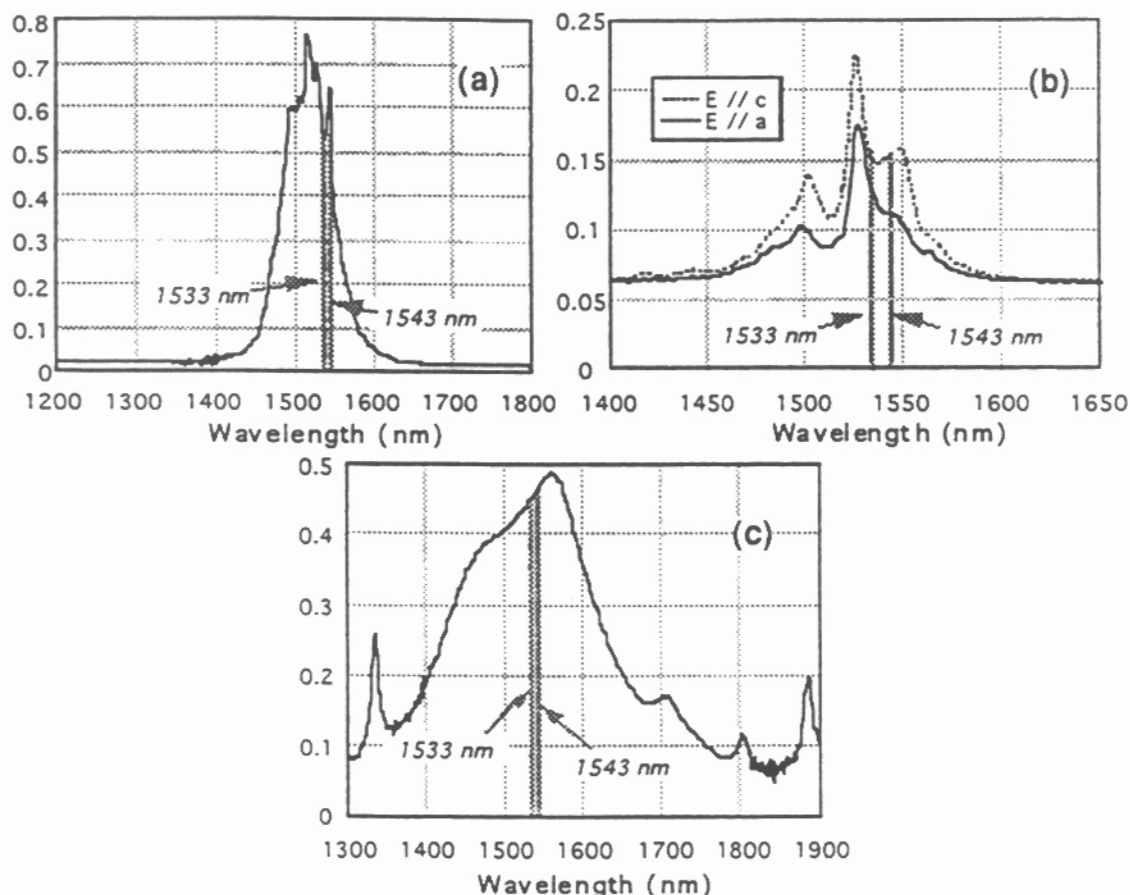


Figure 1. Room temperature absorption spectra of (a) $\text{Er}^{3+}:\text{CaF}_2$; (b) $\text{Er}^{3+}:\text{FAP}$; and (c) $\text{U}^{4+}:\text{SrF}_2$, near $1.53 \mu\text{m}$. Vertical axes are optical density.

Transmittance (T) as a function of incident fluence, for a slowly-relaxing absorber with only saturable losses, is given by the modified Frantz-Nodvik equation:⁷

$$T = \frac{F_{\text{sat}}}{F_{\text{in}}} \ln \left\{ T_0 \left[\exp \left(\frac{F_{\text{in}}}{F_{\text{sat}}} \right) - 1 \right] + 1 \right\} \quad (5)$$

where $F_{\text{sat}} = h\nu/\sigma_a$ is the saturation fluence, F_{in} is the incident fluence, and T_0 is the small-signal transmittance. 1543 nm saturation fluence values of 9.0, 9.8, and 1.9 J/cm^2 were measured for $\text{Er}^{3+}:\text{CaF}_2$, $\text{Er}^{3+}:\text{FAP}$ ($E//c$), and $\text{U}^{4+}:\text{SrF}_2$, respectively. The results are shown in Figures 2 and 3. The 1533 nm cross-sections were found to be approximately 1.3×10^{-20} , 1.4×10^{-20} , and $6.9 \times 10^{-20} \text{ cm}^2$ at 1533 nm, respectively. These values were used in the theoretical modeling.

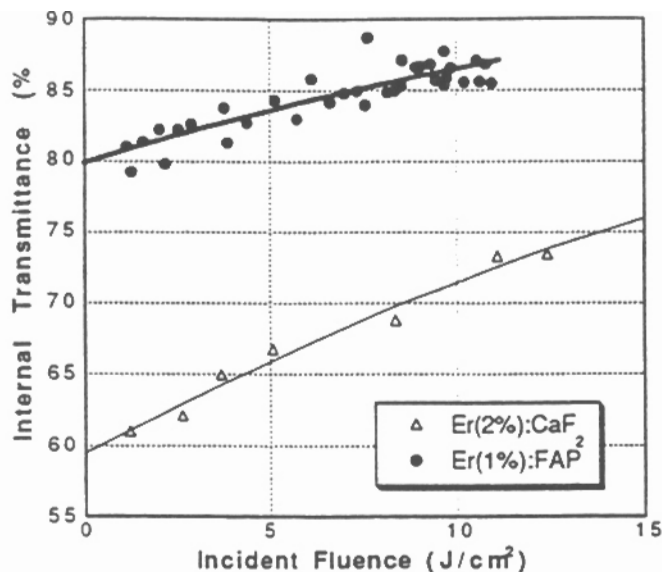


Figure 2. Short pulse bleaching of Er:CaF₂ and Er:FAP at 1543 nm. Solid curves are from modified Frantz-Nodvik theory with saturation fluence 9.2 and 9.8 J/cm², respectively.

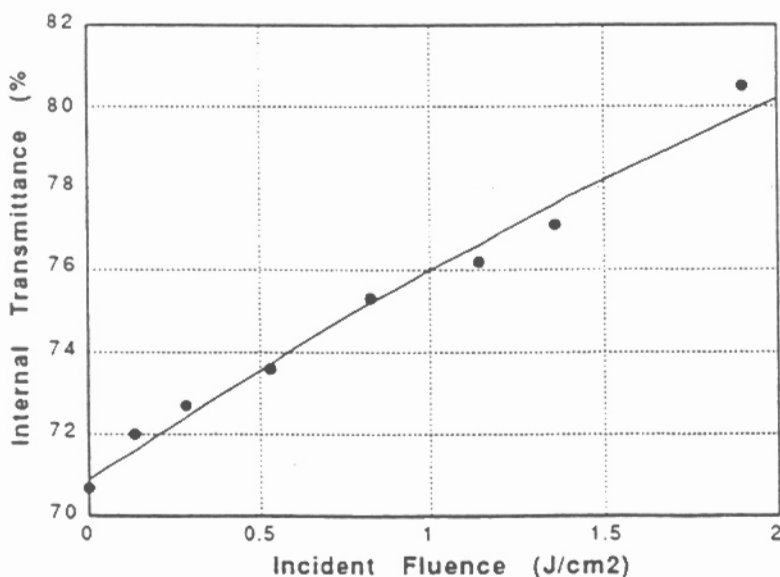


Figure 2. Short-pulse bleaching of U⁴⁺:SrF₂ at 1543 nm. Solid curve is from modified Frantz-Nodvik theory with saturation fluence of about 1.9 J/cm².

3.2 Er:Glass Q-switch experiments

All three materials produced Q-switch pulses near 1533 nm (spectrally narrower than the emission of the free-running Er:glass laser). Both Er:CaF₂ and Er:FAP required intracavity focussing to produce Q-

switch pulses. This is as predicted by relation (4), using the measured absorber cross-sections and $0.8 \times 10^{-20} \text{ cm}^2$ for the stimulated emission cross-section of Er:glass. $\text{U}^{4+}:\text{SrF}_2$ produced Q-switching without focussing, in accordance with equation (4).

The cavity used for the Er:CaF₂ and Er:FAP Q-switches is shown in Figure 4a. The Q-switch was placed near the waist of the beam between the curved output mirror and the positive lens. The resonator cavity used for the $\text{U}^{4+}:\text{SrF}_2$ Q-switch was plane-parallel (Figure 4b). In all cases, we used a (flashlamp-pumped) 3 x 50 mm Kigre QE-7S Er:glass laser rod. The results obtained in saturable absorber Q-switching of Er:glass are summarized in Table I.

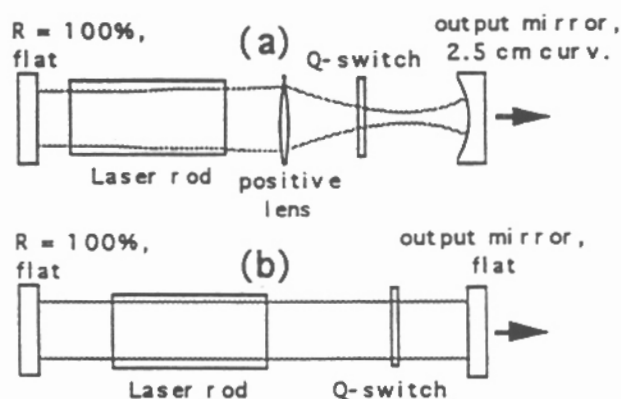


Figure 4. Resonator cavities used for (a) Er:CaF₂ and Er:FAP Q-switches, and (b) $\text{U}^{4+}:\text{SrF}_2$ Q-switch. Focal length of lens in (a) was +5 cm.

Table I. Summary of the saturable absorber Q-switch results.

Q-switch	Thickness (mm)	Output mirror Reflectivity (%)	Output Energy (mJ)	Threshold (J)	Q-switch Pulsewidth (nsec)
(2.0%) Er:CaF ₂	1.0	94 (2.5 cm curv.)	11	51	69
(1%)Er:(1%)Yb: FAP (uncoated)	4.0	80 (2.5 cm curv.)	15	135	43
(1%)Er:(1%)Yb: FAP (AR-coated)	5.0	94 (2.5 cm curv.)	27	44	47
$\text{U}^{4+}:\text{SrF}_2$	2.7	94 (flat)	3	20	60

Equations (1) through (3) were numerically solved using a Runge-Kutta routine. For the case of $\text{U}^{4+}:\text{SrF}_2$, we obtained good agreement between theory and experiment, using the measured cross-section of $6.9 \times 10^{-20} \text{ cm}^2$ and assuming 5% (nonsaturable) cavity losses (see Figure 5). For Er:CaF₂ and Er:FAP, the pulse shape was correctly predicted from theory; however, the pulse energy was considerably lower than

expected. We are still investigating this discrepancy. Er:FAP produced a single Q-switched pulse when the laser was operated just above threshold, but as the input power was increased, the Q-switch pulse was generally followed by several low-power free-running spikes. Neither the Er:CaF₂ nor the U⁴⁺:SrF₂ Q-switches exhibited this behavior.

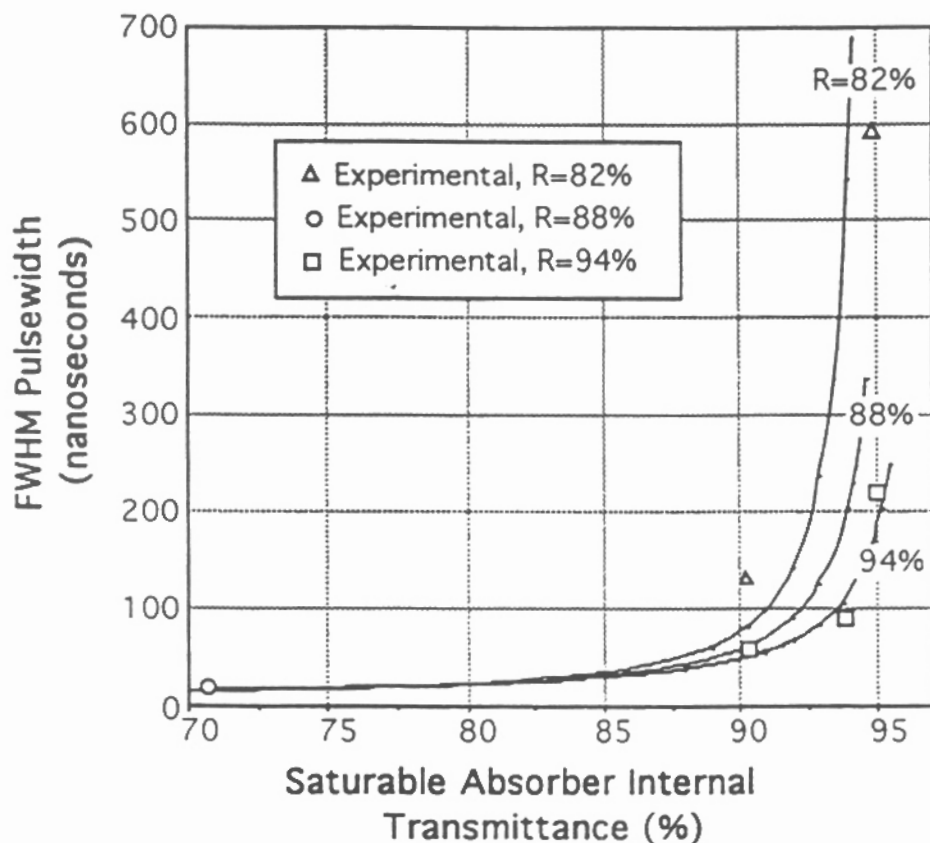


Figure 5. Experimental versus theoretical pulsewidths for U⁴⁺:SrF₂ Q-switches using different output mirror reflectivities. Solid curves are numerical solutions of saturable absorber rate equations.

The saturable absorber Q-switches could be damaged in Q-switched operation. By adjustment of the laser resonator, satisfactory Q-switched operation of the Er:glass laser could be obtained without damage to the Q-switch. An example of the results obtained when the saturable absorber Q-switch is damaged is shown in Figure 6. The sharp cut-off of the pulse, we believe, is due to the onset of damage which blocks or scatters the laser beam.

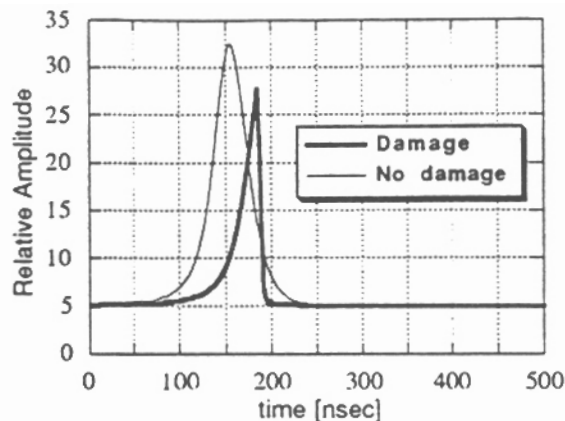


Figure 6. Er:FAP Q-switch pulses with and without the occurrence of Q-switch damage.

4. ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. Robert Sparrow (Optovac, N. Brookfield, MA 01535) who kindly provided the U:SrF₂ and Er:CaF₂ crystals used in this work; and also Dr. Bruce Chai (CREOL, Orlando FL), Dr. Toomas Allik and Dr. Andrew Hutchinson (NVL, Ft. Belvoir, VA) for the Er:FAP crystals. Marly B. Camargo thanks the Brazilian National Science Foundation (CNPq) for her fellowship.

5. REFERENCES

1. H. S. Keeter, D. S. Dewald, and M. A. Woodall, "Report on Repetition-Rated Erbium:Glass Lasers", SPIE Proceedings **1627**, 21 (1992).
2. S. J. Hamlin, J. D. Myers, and M. J. Myers, "High Repetition Rate Q-Switched Erbium Glass Lasers", SPIE Proceedings **1419**, 100 (1991).
3. K. Spariosu, R. D. Stultz, M. Birnbaum, T. H. Allik, and J. A. Hutchinson, "Er:Ca₅(PO₄)₃F Saturable Absorber Q-Switch for the Er:glass Laser at 1.53 μ m", Appl. Phys. Lett. **62**, 2763 (1993).
4. R. D. Stultz, M. B. Camargo, S. T. Montgomery, M. Birnbaum, and K. Spariosu, "U⁴⁺:SrF₂ Efficient Saturable Absorber Q-Switch for the 1.54 μ m Erbium:Glass Laser", accepted for publication in Applied Physics Letters.
5. A. Szabo and R. A. Stein, "Theory of Laser Giant Pulsing by a Saturable Absorber", J. Appl. Phys. **36**(5), 1562 (1965).
6. A. Siegman, in Lasers, (University Science Books, Mill Valley, California, 1986), chapter 26.
7. L. Frantz and J. Nodvik, "Theory of Pulse Propagation in a Laser Amplifier", J. Appl. Phys. **34**, 2346 (1963).